ON THE NATURE AND ORIGIN OF THE STYLOLITIC STRUCTURE IN TENNESSEE MARBLE[1]

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INTRODUCTION

The stone known commercially as "Tennessee marble" constitutes what the government geologists have called the Holston formation, which is of Ordovician age. The quarries are located chiefly in the central portion of the East Tennessee Valley with Knoxville as a center. The marble is sub-crystalline to crystalline in texture and varies in color from light pink and gray to differing shades of red, dark chocolate, and cedar. At present the light pink and gray are the varieties most in demand. The formation is from 200 to 400 feet thick, though by no means is all of this suitable for decorative purposes. As a result of folding, accompanied in places by faulting, the outcrops occur in belts extending from northeast to southwest. The strata dip usually 25 to 35

[1] Read before the Tennessee Academy of Science, November 26, 1915, and the American Association for the Advancement of Science, Pittsburgh, December, 1917. (Abstract, *Science*, New Series, XLVII [1918], 492.)

degrees to the southeast, but in places they are inclined in the opposite direction. The marble takes a fine polish and is much favored by architects for interior decoration. It is widely used for both interior and exterior work and may be seen in many buildings throughout the United States and even in foreign countries.

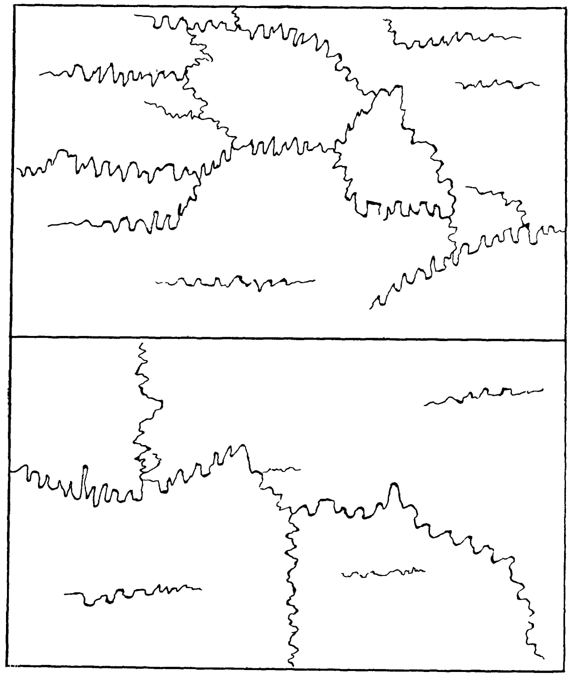

FIG. 1.—Examples of Stylolites in Tennessee Marble

One of the striking features of the marble is the presence of dark-colored, interlocking seams or sutures known technically as "stylolites." This structure, which is prominently displayed on the polished surfaces of slabs cut across the bedding planes of the stone, is known among the quarrymen as "crowfoot" and "toe-nails," and various theories have been proposed to account for it. It first attracted attention in the Muschelkalk of Europe but has been observed to occur in limestones generally, though some of the best examples appear in the Muschelkalk of Europe, the Clinton

limestone of New York, the Bedford limestone of Indiana, and the Tennessee marble.

CHARACTER OF THE PHENOMENA

Early observations, and names applied to it.—According to Rothpletz this structure was first mentioned by Mylius in 1751. In 1807 Friesleben described it as "apfenförmiger Strictur der Flözkalkstein," and later Hausman referred to it as "Stängelkalk." The name "lignilites" was applied to these structures by Eaton in 1824. In 1838 they were called "epsomites" by Vanuxem, who likened them to the sutures of the human cranium, while Hunt gave them the name "crystallites" in 1863. The name "stylolites," from *stulos*, "a column," was given them by Kloden in 1828.

Description of the structure in Tennessee marble.—The sutures present in Tennessee marble have the typical appearance of "stylolites" as described by authors. They consist of slickensided columns of stone projecting alternately from the surfaces on either side of a parting or fracture plane whereby the two parts of the stone become intimately interlocked. As a rule the union is so intricate and firm that the stone will break more readily elsewhere than along the suture. The columns vary in length from a small fraction of an inch to four inches or more, and in diameter they may be two inches or more, though usually they are much under this. The sides of the columns are fluted and striated in the manner characteristic of "slickensides." Occasionally the columns are broad and relatively short with tops studded with the small projections. The columns are usually capped with a thin layer of clay. In places the clay is more abundant and in such cases may weather out in the cliff, leaving cavities. The occurrence of a shell or other fossil capping the column is frequently mentioned by authors but such instances are rare in the Tennessee marble.

In general the sutures are approximately parallel with the planes of bedding, but frequently they may be observed cutting the planes of sedimentation obliquely or even at right angles. In places they appear as a network intersecting the stone in all directions. In some portions of the rock the horizontal sutures are numerous and closely spaced while in others they are several feet apart. In the

majority of cases they thin out without a trace of parting beyond, but not infrequently they are terminated abruptly by a cross-fracture or suture. Branching of the horizontal sutures is common and often the two branches meet again, thus inclosing lens-shaped masses of stone.

On surfaces showing both horizontal and oblique sutures it is observed that the columns are all at right angles to a common plane which is approximately the plane of sedimentation. In their descriptions of stylolites, Marsh, Grabau, and others state that the columns project at right angles from the opposing faces, but this is true, according to our observations, only of those sutures that follow the planes of sedimentation. Where the suture is oblique to this plane the columns are inclined, the inclination being greatest in those sutures which are most oblique to the plane of sedimentation. Where the suture is at right angles to the plane of sedimentation, distinct columns are wanting, the suture appearing as a wavy or zigzag line apparently representing the variety of stylolitic structure termed "pressure-suture" by some authors.

THEORIES OF ORIGIN

Only brief mention will be made here of the earlier suggestions offered in explanation of this structure. Those desiring a fuller treatment are referred to Wagner's exhaustive paper,[1] which includes a fairly complete bibliography of the subject.

Organism theory.—Eaton,[2] who appears to have been the first to offer an explanation of these structures, considered them to be of organic origin and named them "lignilites" in the belief that they were the columns of corals. Four years later, Kloden[3] described them as a distinct species of organism under the name *Stylolites sulcatus*. These, however, had few followers, though Kloden's name "stylolites" has been retained for the structure.

Crystallization theory.—Bonnycastle in 1831 considered the structure as a mineral formed by infiltration. The mineral expla-

[1] Georg Wagner, *Geologische und paleontologische Abhandlungen* (Koken), N.F. (1913), Band XI (XV), Heft 2, pp. 101–27, Plates X, XI, XII.

[2] Amos Eaton, *Geology of New York*, 1824.

[3] F. Kloden, *Die Versteineringen der Mark Brandenburg* (1828), 1834.

nation was accepted in 1838 by Vanuxem and the name "epsomites" applied to the structure in the belief that it represented the crystallization of sulphate of magnesia. Among others who accepted the mineral theory with modifications were James Hall, Ebenezer Emmons, and T. Sterry Hunt, the last named proposing for them the name "crystallites."

Pressure theory.—The first to suggest that this structure is due to differential compression of sediments before consolidation was Quenstedt,[1] followed soon after by Marsh.[2] Experimental demonstration of the theory was attempted by Gumbel,[3] but as Wagner points out the results were not convincing.

Following Marsh's explanation it is assumed that a thick bed of carbonate of lime is deposited as a fine soft ooze over the surface of which are scattered the remains of organisms, such as shells, etc. This is then covered by a very thin layer of argillaceous mud, upon which is deposited more calcareous material, whose increasing weight tends to condense the mass below. As a result of the resistance offered by the shell or other organic substance "the surrounding material will be carried down more rapidly, thus leaving columns projecting above, each protected by its covering and taking its exact shape from its outline." According to this theory, therefore, the structure is due to differences in the amount of compression in the material beneath and around the shell before consolidation as a result of the weight of the overlying mass. The fact that the columns are not always capped by shells (in Tennessee marble rarely), and, further, as pointed out by Grabau,[4] that there is no evidence of deformation, or crowding or squeezing around or above the columns, is against the theory of simple compression either before or after consolidation. Moreover, the fact that the sutures are often oblique or even at right angles to the plane of sedimentation is clearly opposed to this theory. The occurrence of such

[1] A. Quenstedt, *Epochen der Natur*, 1861, pp. 200, 489.

[2] O. C. Marsh, *Proceedings of the American Association for the Advancement of Science*, XVI (1867), 135–43.

[3] Gumbel, *Zeitschr. Deutsch. geol. Ges.*, 1882, p. 642; *ibid.*, 1888, p. 187.

[4] A. W. Grabau, *Principles of Stratigraphy*, 1913, p. 787.

transverse sutures was observed by Marsh, but he seems to have failed to recognize their negative bearing on the pressure theory.

Gas theory.—Zelger,[1] in 1879, after detailed work on the stylolites considers them due to the escape of gases through the soft plastic mass and the later filling in of the passageways.

Erosion theory.—In his description of this structure as it occurs in the Bedford limestone of Indiana, Hopkins[2] reviews the theories given therefor and suggests that some may be due to the formation of cracks in the drying of limestone mud while others look like a rain- or spray-washed surface, though he adds that "possibly the escape of gases, as advocated by Zelger, may have acted in some places."

Solution theory.—The theory that the stylolitic structure is due to unequal solution along suture or fracture planes in calcareous rocks after consolidation was first proposed by Fuchs,[3] later accepted by Reis,[4] and more fully established by Wagner.[5] Quoting from Grabau,[6]

> if solution takes place on the concave surfaces of both the upper and lower faces of the fracture, the result must be the production of a series of tooth-like projections from both sides of the fissure, which, owing to the pressure of the overlying rock, interpenetrate more and more as room is made by solution. In other words the rock opposite the end of each tooth-like projection is dissolved away—the hollows are deepened and the teeth, gliding under pressure, penetrate deeper and deeper into the opposite bed while at the same time they become longer by the deepening of the hollows which surround and isolate them. The residual clay left on solution comes to rest as a cap on the top of the stylolite protecting this top from solution.

The striations on the sides of the stylolite are the result of abrasion between the opposing surfaces in the process of compression. As the sides of the columns are largely free from pressure there is little or no solution there. The presence of a shell or other fossil favors the process, as it is less readily soluble than the inclosing rock.

[1] Zelger, *Neues Jahrb. für Mineralogie*, 1870, p. 833.

[2] T. C. Hopkins, *Twenty-first Annual Report of the Indiana Geological and Natural History Survey*, 1896, pp. 305–8.

[3] T. Fuchs, *Ber. d. K. Akad. d. Wiss. Math. nat. Kl. Wien*, 1894.

[4] O. M. Reis, *Geognost. Jaresh. d. K. Bayr. Obergamtes München*, Band 14, 1901; also Band 15, 1902.

[5] Georg Wagner, *op. cit.*

[6] A. W. Grabau, *op. cit.*

It is held by some that the sutures seen in Tennessee marble represent original stratification planes or partings which are occupied by very thin laminae of silt, and beneath this silt unequal solution has taken place as indicated above. That the opposing faces along clay partings in limestones are affected by unequal solution is a matter of common observation. Often the opposing surfaces of the beds will be seen to have rounded elevations and depressions which alternate with each other, but there is no interlocking as in the case of true stylolites. If the clay parting is very thin, however, it is quite likely that a true stylolitic structure may develop along such planes, and that some of the sutures in Tennessee marble are of this character is probable. But from the study of hundreds of examples of the sutures in the Tennessee marble, the writer is convinced that in the main they represent fracture planes. Convincing proof of this appears in their irregularity and frequent tendency to cut across the sedimentation planes obliquely or even at right angles. Wagner, who described them as occurring along fractures, stressed this point when he says that, whereas under the pressure theory the sutures must follow the plane of sedimentation, in the solution theory they may intersect the stone in any direction.

Inasmuch as the columns manifest a general tendency to assume a position at right angles to the plane of sedimentation and since it is probable that static as opposed to dynamic pressure has been most effective in furthering solution this would seem to offer evidence that the stylolitic structure was more or less advanced if not completed before the rocks assumed their present tilted position as a result of folding and faulting at the close of the Paleozoic era.

Grabau considers that the length of the column is a fair measure of the amount of material removed from both sides of the fracture.

SUMMARY

Polished slabs of Tennessee marble are usually marked by irregular zigzag lines likened by Vanuxem to the sutures of the human skull and now known generally as "stylolites," the origin of which is a subject of frequent inquiry. These structures consist of striated

toothlike projections or columns projecting from the opposing surfaces along a plane of fracture whereby the two parts of the stone are so intimately interlocked that often the slab will break more readily elsewhere than along the suture.

The theory that they are due to differential compression in beds of soft calcareous sediments separated by a thin film of clay was first proposed by Quensted (1861) and adopted by Marsh (1867), Gumbel (1882), Rothpletz (1900), and others. The absence of evidences of compression and squeezing as also the fact that the sutures are often more or less oblique to the planes of sedimentation or may form a network of intersecting lines are adverse to this theory.

The most satisfactory explanation of these remarkable structures is the solution theory first proposed by Fuchs (1894) and ably supported by Reis (1901, 1902) and Wagner (1913). According to this theory the structures are due to unequal solution along planes of fracture, or extremely thin partings after the consolidation of the rock. As the result of compression due to the weight of the overlying mass, solution will take place more rapidly on the concave surfaces opposite the columns, thus causing these to penetrate deeper and deeper into opposing surface. The residual clay comes to rest as a cap on the top of the column, thus protecting it from solution. Fossil shells sometimes found on top of the column favor the process, as they are less readily soluble than the inclosing rock.